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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re PATENT APPLICATION of :

Leslie Michael LEA et al. :

Serial No.: 10/043,265 : Group Art Unit: 1746

Filed: January 14, 2002 : Attorney Docket No.: WLJ.056CIP

For: PLASMA PROCESSING APPARATUS

CLAIM OF PRIORITY

Honorable Assistant Commissioner for Patents and Trademarks,
Washington, D.C. 20231

Sir:

Applicants, in the above-identified application, hereby claims the priority date under the International Convention of the following British application:

Appln. No. 0100958.8 filed January 13, 2001

as acknowledged in the Declaration of the subject application.

A certified copy of said application is being submitted herewith.

Respectfully submitted,

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Date: August 21, 2002

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15JAN01 E597887-1 D01559
P01/7700 0.00-0100958.8

Request for grant of a patent

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Cardiff Road
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1.	Your reference	MJ/CS/STS.39
2.	Patent application number *(The Patent Office will fill in this part)*	**0100958.8** 13 JAN 2001
3.	Full name, address and postcode of the or of each applicant *(underline all surnames)*	Surface Technology Systems Limited Imperial Park Newport Gwent NP1 9UJ
	Patents ADP number *(if you know it)*	55341 51002
	If the applicant is a corporate body, give the country/state of its incorporation	United Kingdom
4.	Title of the invention	Plasma Processing Apparatus
5.	Name of your agent *(if you have one)*	Wynne-Jones Laine & James
	"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	22 Rodney Road Cheltenham Gloucestershire GL50 1JJ
	Patents ADP number *(if you know it)*	1792001

		Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*
6.	If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number			

		Number of earlier application	Date of filing *(day / month / year)*
7.	If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application		

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? *(Answer 'Yes' if:* — Yes

a) any applicant named in part 3 is not an inventor, or
b) there is an inventor who is not named as an applicant, or
c) any named applicant is a corporate body.
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Continuation sheets of this form	
Description	19
Claim*(s)*	
Abstract	
Drawing*(s)*	4 + 4

10. If you are also filing any of the following, state how many against each item.

Priority documents	
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Statement of inventorship and right to grant of a patent *(Patents Form 7/77)*	
Request for preliminary examination and search *(Patents Form 9/77)*	
Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(please specify)*	

11. I/We request the grant of a patent on the basis of this application.

Signature Wynne-Jones Laine & James — Date 12.01.01

WYNNE-JONES LAINE & JAMES

12. Name and daytime telephone number of person to contact in the United Kingdom — Mr. M. James 01242 515807

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Notes

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"Plasma Processing Apparatus"

Plasma may be produced in a first chamber, with the ions and radicals created being allowed to diffuse into a second chamber where etching of, or deposition on, a silicon wafer or other workpiece may take place. This is the concept of a de-coupled plasma source and process chamber. It is frequently advantageous to produce a dense plasma so that there are large numbers of radicals available to increase the rate of the required chemical process, etch or deposition. However, in general, when a dense plasma is created, in addition to a large number of radicals, large numbers of ions will be produced which may contribute to damage of or other undesirable effects on a silicon wafer or other workpiece.

According to a first aspect of the invention there is provided a plasma processing apparatus comprising a first chamber provided with a plasma inducing device designed to produce a plasma in said first chamber, and a second chamber into which plasma so produced can diffuse to act upon a workpiece being processed, and a magnetic field production device positioned relative to at least the first of said two chambers to influence ion diffusion into the second chamber and in relation to the workpiece.

The control measures incorporated into the system by the magnetic field device, adjust the relative numbers of ions to radicals, which diffuse into the second chamber and reach the wafer. Thus, the use of suitably orientated

magnetic fields will influence ion diffusion while not affecting the diffusion of neutral radicals.

Preferably the magnetic field production device would comprise permanent magnets or electromagnets installed around the side wall of the first chamber, and optionally also around the side wall of the second chamber. Preferably the magnetic field production device around the first chamber will be a solenoid whose output can be varied. For the second chamber a solenoid device (whose output also may be variable) is ideally provided at a position to create a magnetic field inside the second chamber at the level of the workpiece.

The second chamber may be provided with a magnetic bucket arrangement created by an array of magnets around the chamber wall. A magnetic structure might also be formed at the junction of the two chambers to create a dipole magnetic field there.

The first chamber geometry could be formed as a cylinder, a stepped cylinder, a cone, a truncated cone, or a hemisphere, or a combination of these geometries.

According to a further aspect of the invention there is provided a plasma processing apparatus comprising a first chamber provided with a plasma inducing device designed to produce a plasma in said first chamber, and a second chamber into which plasma so produced can diffuse to act upon a workpiece being processed, wherein the first chamber is formed of two or more differing-diameter

cylindrical dielectric sections, one above the other, each such section being provided with its own plasma inducing device.

The portions joining the individual sections of said first chamber can be formed of metallic or dielectric material and can be perpendicular to or angled to said sections.

Such a multi-section chamber can form part of the apparatus of the first aspect of this invention, in which case it can have a magnetic field production device associated with one or more of said sections.

The control measures may be required to have a functional dependence on time or another parameter, which may be linked to a particular aspect of the etch or deposition process. For example the number of ions reaching a surface being etched may be required to decrease once a surface layer has been removed, while the number of radicals reaching the surface may be required to remain constant. The level of the control measures can be re-adjusted after a given time in which the surface layer has been removed, in order to achieve the new desired ratio of radicals to ions. The control measures may also incorporate a spatial dependence, so that the relative number of ions to radicals can be varied as a function of position on the wafer.

For the etching of deep trenches in silicon or other suitable materials, a switched process may be used (Robert

Bosch GmbH US5501893 or Surface Technology Systems Ltd US6051503). In such a process, alternating steps of material deposition and etch occur, with the resultant anisotropic etching of features into the wafer. In greater detail, a polymer is deposited on both the sides and bottom of a trench or other feature during the deposition step. During the following etch step, the polymer is preferentially removed from the bottom of the trench by directed ion bombardment, then allowing a chemical etch of the exposed silicon. Although the chemical etch is essentially isotropic, the overall etch process is anisotropic, because the polymer removal is only from the bottom of the trench, and the silicon etch depth is small for each etch step. A suitable patterned mask of, for example, photoresist is applied to the wafer before the etch process is started in order to define the surface geometry of the features to be etched. It is an important aspect of the overall process, particularly for deep trench etching, that the ion bombardment utilised to remove the polymer from the bottom of the trench, does not erode the mask before the required depth of etch has been achieved, otherwise the definition of the features will be lost.

A number of different arrangements of permanent and electromagnets have been described in our International Patent Application PCT/GB99/04168, to allow control of the relative numbers of ions to radicals which are permitted to reach the wafer. In regard to a switched etch process, the

field produced by any electromagnet may be adjusted to one level for the etch step and to a different level for the deposition step. In some circumstances it may be advantageous to vary the field strength during either or both of the etch and deposition steps. For example during the etch step, the magnetic field strength may be kept low during the early part, in order to allow a high flux of ions to reach the wafer and remove the polymer which has been deposited on the bottom of a trench. When the polymer has been removed, the field strength can be increased to reduce the ion flux to the wafer and so reduce the mask etch rate. In addition to this, the field may be adjusted from one etch step to the next etch step, and/or from one deposition step to the next deposition step, in order gradually to adjust the relative numbers of ions to radicals as the trench etch proceeds.

This Application describes in detail, features of a plasma processing apparatus which enable a high etch rate to be achieved with good uniformity in the etch rate across the wafer and precise control of the shape of etched features. In this Application, the description is particularly directed towards etching carried out by means of a switched process as described above. This is not intended to preclude the application of aspects of the system to either a continuous etch process or a continuous deposition process (the term "continuous" in this context referring to the feature that the process is "not switched

between etch and deposition steps", rather than any implication that the process rate, or other aspect, remains constant in time).

The plasma processing apparatus consists of two or more chambers. In the second chamber, usually the larger, a silicon wafer or workpiece is mounted on a suitable support. This support may incorporate features to allow cooling or heating of the wafer during, before or after processing. The support may also allow an RF or DC voltage, continuous or pulsed, to be applied to the wafer with respect to the chamber, to enable ions to be accelerated to the wafer. Features may be incorporated in the support and in the chamber wall to allow remote loading or un-loading of the wafer. Ports will usually be incorporated in the walls of this chamber for pressure gauges and other diagnostics, with a relatively large port or ports through which gas exits to the vacuum pumping system used to maintain the desired operating pressure in the chamber.

The first chamber or chambers will typically be of smaller volume than the second chamber in which the wafer is mounted. Plasma is created and sustained in this first chamber and ions and radicals diffuse into the second chamber. Control means, such as a magnetic attenuator, may be used to define the flow of ions and radicals into the second chamber. Reference to one chamber does not preclude the use of multiple chambers in which plasma is formed, with multiple control means to control the flow of ions and

radicals into the second chamber in which the wafer is mounted. When plasma is formed in multiple first chambers there is no restriction implied on whether all chambers are operating at the same time, whether feed gases are the same, or whether the level of power input to each plasma is the same.

The invention may be performed in various ways and preferred embodiments thereof will now be described, by way of example with reference to the accompanying drawings, in which:-

Figure 1 is an illustration of a form of de-coupled plasma source and process chamber of this invention;

Figure 2 is a horizontal cross-section through the chamber of Figure 1;

Figures 3A to 3C illustrate possible alternative geometries for the shape of the first chamber of the system shown in Figure 1;

Figure 4 shows a further possible geometry for the first chamber of the system in Figure 1 and a magnetic field created therein; and

Figure 5 shows the magnetic field created in a modified form of the system in Figure 1.

The system of a single first chamber A in which plasma is produced and allowed to flow into the second chamber B, in which the wafer is located, is shown diagrammatically in Figure 1. The wafer 1 is mounted on a wafer support 2 in the lower chamber B. Good thermal contact is maintained

between the wafer and a temperature-controlled section of the support by means of mechanical clamping of the wafer, or by electrostatic clamping, or by other means appropriate to the situation. A thin layer of pressurised gas such as helium, injected through an inlet 3, may be used to fill the small gap between the back of the wafer and the support in order to improve the conduction of heat between the two surfaces. The appropriate parts of the support may be connected to an RF or DC, continuous or pulsed voltage, power supply, for example the RF supply 4, via a suitable impedance matching unit 5, to create a controlled potential difference across the sheath formed above the wafer, thereby controlling the energy of ions impinging on the wafer. The normal processing height within the chamber is indicated at 6. Gas is evacuated through a pumping port 7.

Permanent magnets 21 (as shown in Figure 2) may be installed around the sides of chamber B (and chamber A if appropriate) in columnar form to define a "magnetic bucket". A "multi-cusp" or "picket fence" arrangement serves to reduce the diffusion of ions and electrons to the walls of the chamber. Historically a "magnetic bucket" configuration has been utilised to increase the plasma density within a chamber because, for a given rate of production of ions and electrons within the volume, the rate of loss to the walls is reduced compared with the situation in which the "magnetic bucket" is not present. If magnetic confinement is provided for chamber A, it is

primarily to serve this purpose and allow a high density plasma to be formed with a high density of neutral radicals.

Where there is a requirement to reduce the number of ions reaching the wafer compared with the number of radicals, it would at first sight appear illogical to add magnetic confinement to chamber B, since those ions which diffuse into chamber B will be confined more effectively than if the "magnetic bucket" had not been present. For chamber B, however, the purpose of providing magnetic confinement is primarily to increase the uniformity of the ion flux that reaches the wafer. With no magnetic confinement around chamber B, diffusion of plasma from chamber A down into chamber B, results in ions and electrons being lost to the walls of chamber B, before reaching the wafer position. The plasma density decreases with distance from chamber A to the wafer, and becomes increasingly non-uniform with the highest density on the axis of the chamber. Magnetic confinement around chamber B reduces the loss of plasma to the walls, and therefore ensures that the uniformity of the plasma at the wafer position is considerably increased. The proposal for magnetic confinement around chamber B is not intended to preclude the use of a system in which there is no magnetic confinement around chamber B. That is the "magnetic bucket" is only utilised when there is an advantage in so doing.

In order to obtain high numbers of neutral radicals at the wafer position, with low numbers of ions, but with good spatial uniformity of the ions, it is necessary to provide good confinement of ions within chamber B, but at the same time significantly reducing the number of ions diffusing out of chamber A compared with the number of radicals. A magnetic plasma attenuator integral with chamber A, or between the two chambers, may therefore be used in conjunction with the plasma confinement in chamber B to achieve the required result. A dipole magnetic plasma attenuator for this purpose may be formed by a permanent magnet or electromagnet.

At the level where the wafer is processed, a solenoidal magnetic field is desirably formed inside the chamber by an electromagnet 9 located either outside (as shown) or inside of the chamber. The strength of the field may be controlled such that it is of a different value during separate steps of a switched process, and in addition may be ramped in value either up or down for either respective step as the process progresses. The purpose of this field is to assist in the control of the directionality of the ions reaching the wafer surface and in the uniformity of the ion flux across the surface of the wafer.

The process plasma is formed in the upper chamber A. For the remainder of this description reference will be to a plasma created and sustained by the inductive coupling of

radio frequency power. This does not, however, preclude the use of other means to form the plasma, such as by the use of microwaves, (including in the form of electron cyclotron resonance), helicon waves, or DC means with and without a heated filament as an electron source. In Figure 1 an antenna 10 is shown located around a cylindrical tube 11 of dielectric material, through which RF power is inductively coupled into the plasma formed inside the tube. The tube geometry can be other than that shown, for example square or hexagonal or other shape in cross-section. The geometry may alternatively take the form of a cone 11A, truncated cone 11B or hemisphere 11C or combination of these geometries (Figure 3). In most circumstances, one antenna 10 will be used to couple power into the plasma. However, the uniformity of the etch or deposition process may be improved by the use two or more antennae 10A, 10B, particularly if they are located around different diameter sections of the dielectric tube 11 (Figure 5).

The dielectric material from which the tube 11 is formed may be alumina or quartz or other suitable material compatible with the process gases. It may be advantageous to use a material such as silicon carbide, which has higher thermal conductivity than alumina, and therefore enables better transference of heat from the internal walls, adjacent to the plasma, to external cooling means. Because of its higher electrical conductivity, silicon carbide may

assist in reducing the capacitive coupling of RF power into the chamber when inductive coupling is the desired mode. Aluminium nitride is an alternative material, combining high thermal conductivity with low electrical conductivity, and allowing good heat transference but with little effect on the coupling of RF power from an external antenna 10 into the plasma. When the plasma density is high, the high thermal conductivity of either aluminium nitride or silicon carbide can be a particular advantage. This is because the temperature gradient between the inside and outside of the tube is reduced compared with a material with less good thermal conductivity such as alumina, and therefore differential expansion of the tube is reduced. Significant differential expansion of the dielectric tube can lead to crack formation and propagation, with loss of vacuum integrity.

In some circumstances there may be advantages in terms of the uniformity of processing of the wafer, to use a geometry (see Figure 5) in which chamber A is formed of two, or more, differing-diameter cylindrical dielectric sections 11X, 11Y. RF power is then coupled into the plasma by two, or more, separate antennae 10A, 10B each located around the respective cylindrical sections. This may be constructed out of one piece of dielectric material, or may consist of two, or more, separate sections 11X, 11Y with a conducting or non-conducting interface flange 12 with appropriate vacuum sealing means. Although

cylindrical sections are described, this is not to preclude other geometrical shapes such as those with square or hexagonal cross-sections. The two, or more, separate antennae would utilise separate impedance matching units and either separate RF power supplies or a split output from a single supply. With reference to Figure 5, the power coupled into the plasma via antenna 10A has more effect on the ion and radical fluxes reaching the centre of the wafer, while the power coupled into the plasma via antenna 10B has more effect on the ion and radical fluxes reaching the outer region of the wafer. Lateral diffusion of ions and radicals means that the above effect is not clear cut, but is essentially true if the distance between the upper chamber A, and the wafer is not too great. Adjustment of the relative levels of RF power fed to the two, or more, antennae would allow adjustment of the plasma profile within this chamber, and of the effect of the plasma at the wafer. Relative power levels could be adjusted to different values depending on whether an etch step or a deposition step was in progress.

With reference to Figure 1, the upper chamber A is formed out of the dielectric cylinder 11 defining the side walls, with the top closed by plate 13 with suitable vacuum sealing means to the cylinder. The top plate will normally be constructed out of metal, with a suitable connection 14 to allow process gas to be fed into the chamber. Suitable means may be incorporated to distribute the gas uniformly

in the chamber. A window (for example as at 15 in Figure 5) may be incorporated in the top plate to allow observation of the plasma and/or wafer for process end-point measurements etc. The lower end of the dielectric cylinder interfaces with the lid of the lower chamber B, either directly or with an intermediate short pipe section, usually formed of metal, which may be grounded or allowed to float electrically or biased to a chosen potential.

Although the above description includes the feeding of process gas through the lid of the upper chamber A, it may under certain circumstances be desirable, additionally or alternatively, to feed gas back up into this chamber from a gas ring 16 mounted within the lower chamber B, near the lid 17 of the lower chamber. In some circumstances one gas may be fed through the lid of the upper chamber A and a different gas may be fed from the gas ring mounted within the lower chamber B. Where the geometry of the upper chamber is a hemisphere or cone, manufactured entirely out of dielectric material, then it will not be possible to feed gas into the top of the upper chamber A and a gas ring within the lower chamber is then essential.

For a plasma to be formed in the upper chamber A, RF power must be applied to the antenna 10 surrounding the upper chamber with the required process gas introduced via the relevant inlet means. Neutral radicals are formed by energetic electrons from the plasma impacting on the neutral gas and, therefore, within the upper chamber A,

ions, electrons, radicals and un-dissociated feed gas will exist. All of these species will diffuse into the lower chamber B, with some losses in numbers due to re-combination in the volume and at the walls. Ions and electrons will re-combine readily at the walls of the chamber; however radicals may survive a number of collisions. When magnetic confinement is present in the lower chamber B, the loss of ions and electrons to the walls of this chamber can be significantly reduced.

Restriction of the size of the aperture in the lid of the lower chamber, where the upper chamber is mounted, or the internal diameter of the intermediate short pipe section when present, will allow a higher pressure differential to be maintained between the upper chamber and the lower. This may increase the process efficiency because the higher pressure in the upper chamber can benefit the formation of ions and radicals because of increased collisions, while a reduced pressure in the lower chamber reduces the incidence of re-combination within the volume. This arrangement can clearly only be utilised when there is a gas feed into the upper chamber, and may have detrimental results if losses of ions or radicals at the restriction are increased. A variable aperture automatic pressure control (APC) arrangement may be incorporated at this position. However the physical design of the APC may reduce the uniformity of the ion flux, in particular, reaching the wafer.

If desired, a dipole magnetic field, either formed by the use of permanent magnets 8 or an electromagnet, may be applied across the lower end of the upper chamber A (or across the intermediate short pipe section when present), to form a magnetic plasma attenuator. The permanent magnets or electromagnets used to create the field will generally be located outside of the chamber, but may be partially or wholly internal to the chamber. The action of this field is to deflect electrons, and thence ions, to the wall where they are lost, and therefore to allow control of the numbers of ions passing into the lower chamber, whilst not reducing the radical flux.

If the magnet structure is inside the chamber, then by its geometry it will be expected to increase slightly the local loss area for radicals. Control of the relative numbers of ions compared with radicals, passing into the lower chamber, allows greater control of the overall process. In particular for a switched process, if an electromagnet or hybrid of a permanent and an electromagnet is utilised, then it is feasible to control the relative numbers of ions to radicals to different appropriate ratios for each of the two steps.

Control of the RF power into the plasma in the upper chamber A determines the numbers of ions and radicals formed, and in general both will increase with increasing power input. Process gas flow and pressure will also have an effect. There is increasingly a need to produce higher

etch rates, which for chemical reactions requires large numbers of radicals while the numbers of ions may need to be restricted to reduce unwanted damage to the etched structure or the mask. The combination of control of the plasma density to produce large numbers of ions and radicals, in conjunction with a "magnetic plasma attenuator" to reduce the ion component reaching the wafer, permits high, predominantly chemical, etch rates to be achieved with reduced ion-associated detrimental effects. Detrimental effects associated with high ion fluxes to the wafer include high mask etch rates and problems in sidewall profile control of etched features.

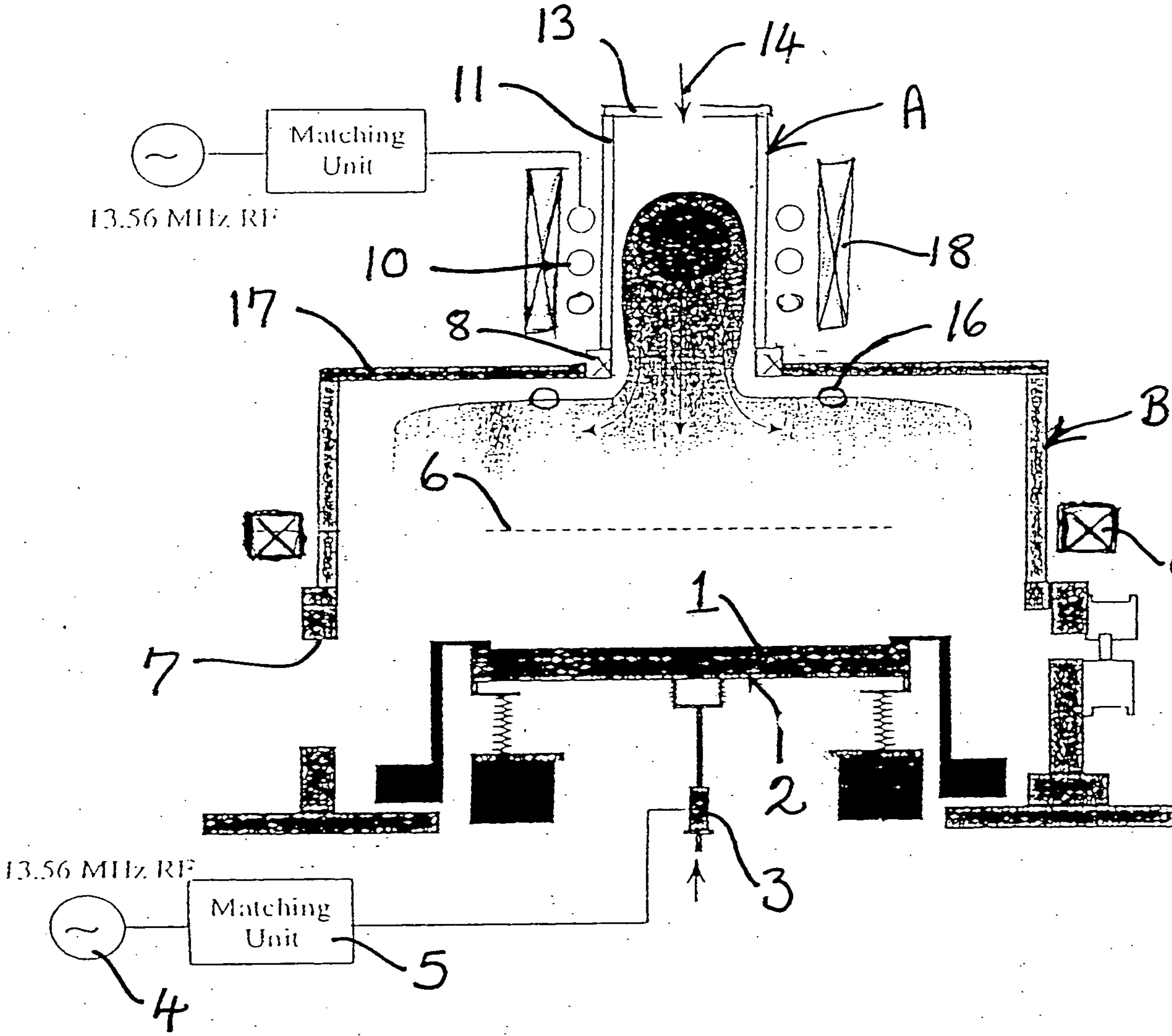
The dipole form of "magnetic plasma attenuator" has a drawback in that the application of a magnetic field across the upper chamber leads to a perpendicular deflection of ions and electrons such as to reduce the cylindrical symmetry of the ion flow from the region in which the plasma is formed, down towards the wafer. This may reduce the uniformity of the process carried out on the wafer.

A solenoidal magnetic field generated by a coil 18 around the upper chamber A, as shown in Figure 4, has advantages as a "magnetic plasma attenuator", over the dipole field described above. Cylindrical symmetry is maintained while, by judicious adjustment of the magnetic field strength, a dense plasma region 19 formed inside the tube 11 and adjacent to the antenna 10 is at least partially trapped by the field lines 20. These field lines

intersect the wall of the upper chamber A near or on the lid 13, and either on the upper chamber wall near its base, or on the lid 17 or upper walls of the lower chamber B. The omission of a magnet 8 (creating a dipole field) removes a possible source of non-uniformity of the plasma. Significant numbers of radicals can be created in the upper chamber A, which then diffuse into the lower chamber. The associated ion flux is reduced, however, because of losses where the field lines intersect the walls, thereby ensuring that the ratio of ion numbers to radical numbers reaching the wafer is reduced in line with requirements. As shown in Figure 5 there may be separate solenoids 18A, 18B provided for each of the sections 11X and 11Y, which allow for greater control of the plasma. As can be seen separate dense plasma regions 19A and 19B are created by the two antennae.

When magnetic confinement is provided in the lower chamber B, some electrons trapped on magnetic field lines from the solenoid 18 around the upper chamber A, may encounter the strong magnetic fields at the walls of chamber B. This may lead to some local mirroring of the electrons so that they may survive to take part in further excitation and ionisation collisions with gas molecules. The situation may occur therefore where the strength of the field from the solenoid around the upper chamber A is sufficient to reduce significantly the flux of ions to the wafer 1, whilst at the same time excitation and ionisation

collisions are increased. An increased rate for radical formation by this mechanism has the potential to increase the rate of chemical etching of the wafer.


13
14
11
A
Matching Unit
13.56 MHz RF
10
18
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2
3
13.56 MHz RF
Matching Unit
5
4

FIG. 1

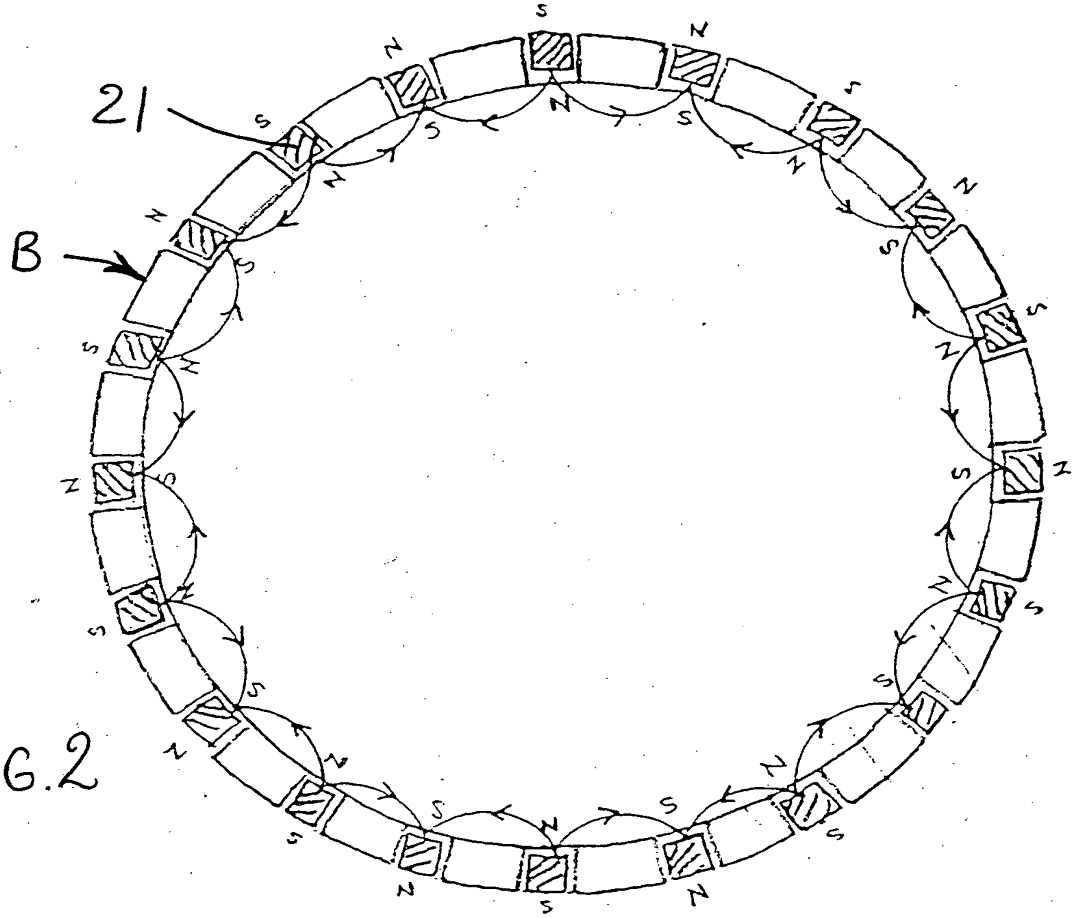

FIG.2

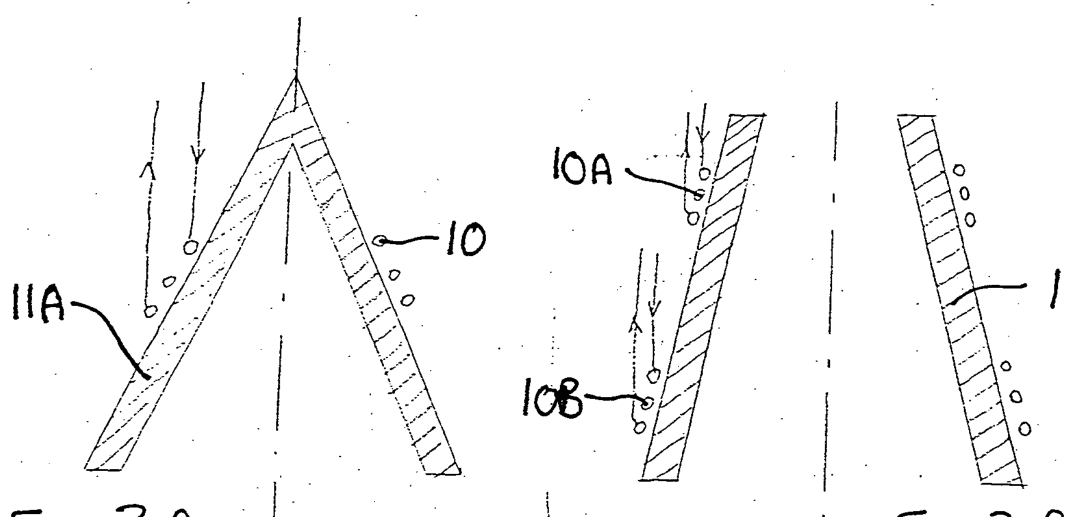

FIG.3A

FIG3B

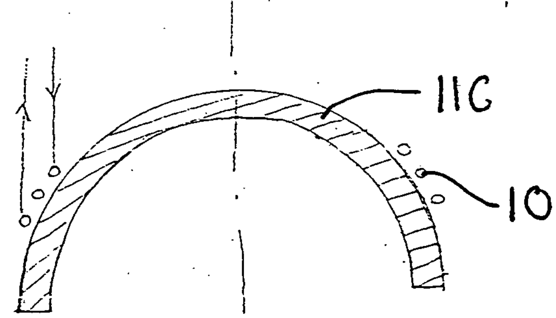

FIG.3C

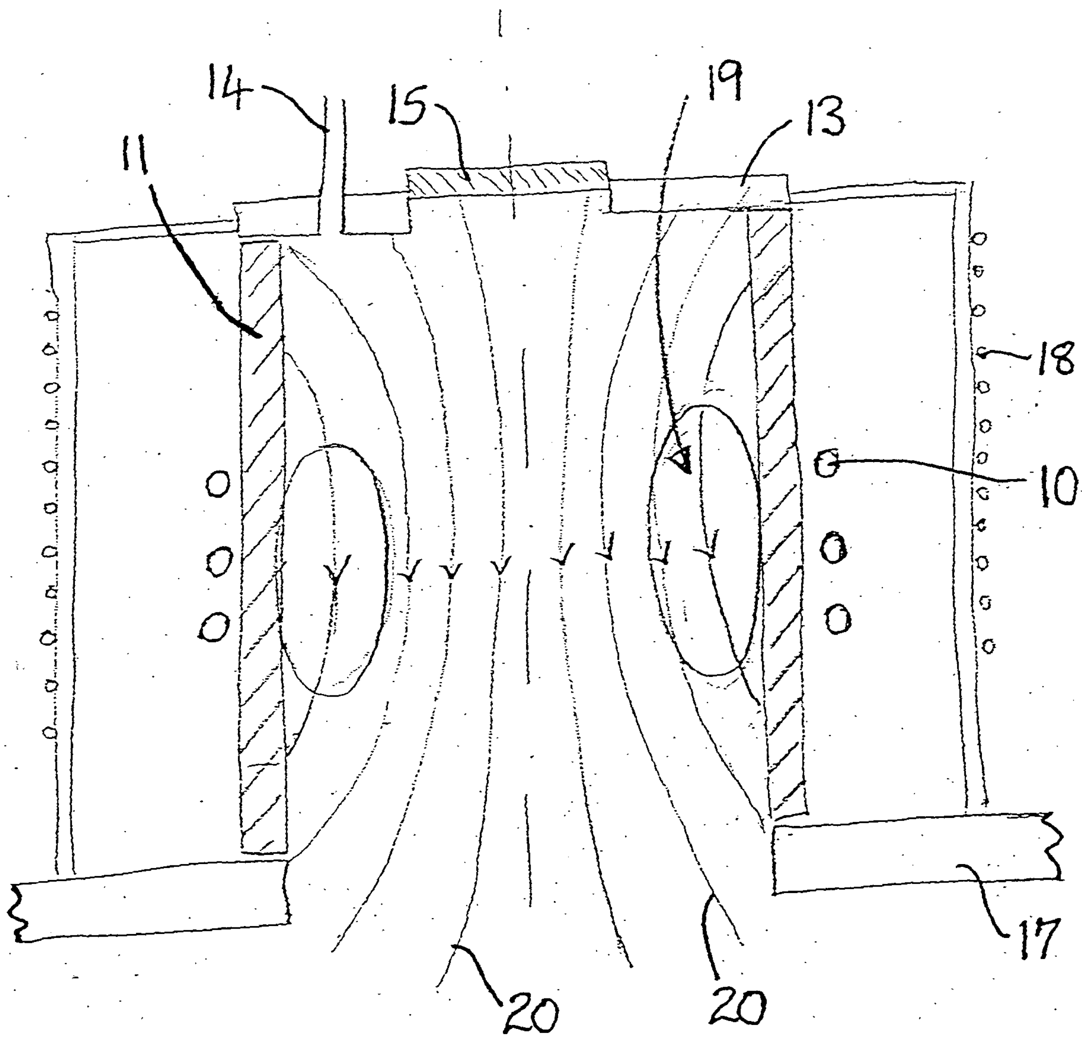

FIG. 4

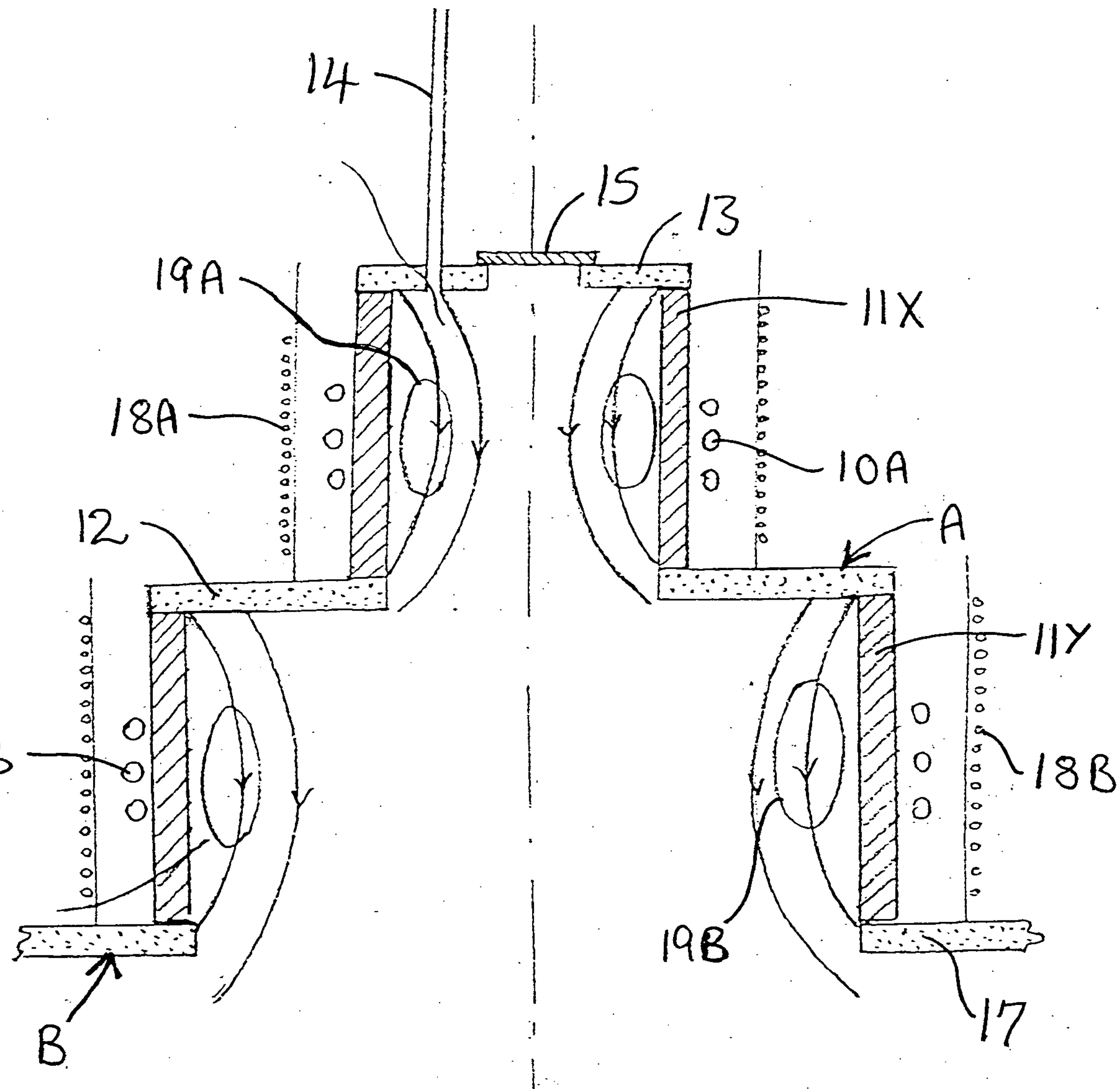

FIG. 5